The Effect of the Ionosphere on Remote Sensing of Sea Surface Salinity From Space: Absorption and Emission at L Band

David M. Le Vine, *Fellow, IEEE,* and Saji Abraham, *Member, IEEE*

***Abstract*—The purpose of this work is to examine the effects of Faraday rotation and attenuation/emission in the ionosphere in the context of a future remote sensing system in space to measure salinity. Sea surface salinity is important for understanding ocean circulation and for modeling energy exchange with the atmosphere. A passive microwave sensor in space operating near 1.4 GHz (L-band) could provide global coverage and complement in situ arrays being planned to provide subsurface profiles. However, the salinity signal is relatively small and changes along the propagation path can be important sources of error. It is shown that errors due to the ionosphere can be as large as several psu. The dominant source of error is Faraday rotation but emission can be important.**

***Index Terms*—Ionospheric electromagnetic propagation, microwave radiometry, ocean salinity, remote sensing.**

I. Introduction

THE SALINITY of the open ocean is important for understanding ocean circulation and for modeling energy exchange with the atmosphere. For example, salinity gradients affect mixed layer processes, which influence fluxes of heat near the surface [1]. Salinity and temperature determine water density and are important factors in large-scale ocean circulation [2]. Also, changes in salinity are primarily caused by changes in freshwater (evaporation, precipitation, melting ice, or river input). These changes are manifestations of elements of the water cycle, which are poorly known over the ocean [3].

Microwave remote sensing from space could provide the necessary temporal and spatial sampling needed to understand the role of salinity in these ocean processes [2], [4]. Changes in salinity modulate the emissivity of the surface and cause changes in emission that are sufficiently strong in the low frequency portion of the microwave spectrum to be detected with passive sensors [5], [6]. Measurements from space have been proposed [7] and salinity differences were observed from space with the L- band radiometer on SKYLAB 25 [8]. Recently, experiments with L-band radiometers on aircraft have demonstrated that salinity can be retrieved with accuracy useful for studying processes in coastal regions [9], [10].

However, measurement of sea surface salinity (SSS) in the open ocean presents a special challenge. This is so because the dynamic range of SSS in the open ocean is relatively small (about 5 K) and the requirements for a scientifically useful measurement (about 0.05 K) put a severe constraint on radiometric performance. A change of 0.05 K at L-band corresponds to a change of about 0.1 psu [7] where "psu" denotes changes measured on the practical salinity scale [11]. To put the challenge of this measurement in perspective, the dynamic range associated with changes in soil moisture is on the order of 100 K [12] and measurement requirements are 1–4 K [13].

Among the important potential sources of error at L-band is the ionosphere. The ionosphere causes a change in the direction of polarization (Faraday rotation) and because the ionosphere is lossy at L-band, there is both attenuation and emission along the signal path. As will be shown here, both phenomena can cause errors that are important for remote sensing of salinity at the 0.1-psu level of accuracy. A brief background is given in Appendices A and B to define Faraday rotation and attenuation in the ionosphere. In Section II, the magnitude of Faraday rotation and its effect on observed brightness temperature are presented. In Sections III–IV, attenuation and its effect on brightness temperature (emission) are discussed.

II. Faraday Rotation

A. Magnitude

The rotation of the polarization vector in the ionosphere is due to the change along the propagation path from surface to sensor of the phase, Ω, in (B3). Substituting (A6) into (B4) and integrating along the propagation path, s, one obtains

$$\Omega_F = \left(\frac{\pi}{c\nu^2}\right) \int \nu_p^2(s)\nu_B(s)\cos\left(\Theta_B(s)\right) \mathrm{ds} \qquad (1)$$

where Ω_F is the Faraday rotation in radians and Θ_B is the angle between the direction of propagation and the Earth magnetic field [14], [15]. To simplify the many calculations needed to make a global map of Ω_F, (1) has been approximated by making the change of variables $\mathrm{ds} = \sec(\theta)\mathrm{dz}$ where z is the normal to the surface at the subsatellite point nadir and θ is the polar angle between nadir and the line of sight to the surface (incidence angle). Substituting for the plasma frequency, ν_p and electron gyro frequency, ν_B, from (A2)–(A3) and replacing B by its value at an altitude of 400 km [16], one obtains

$$\Omega_F \approx 6950\, B(400) \cos\left(\Theta_B\right) \sec(\theta)\mathrm{VTEC}. \qquad (2)$$

Manuscript received June 1, 2001; revised December 13, 2001.

D. M. Le Vine is with the Microwave Sensors Branch/Code 975, Laboratory for Hydrospheric Processes, Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: dmlevine@priam.gsfc.nasa.gov).

S. Abraham is with the Science System and Applications, Inc., Microwave Sensors Branch/Code 975, Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: sabraham@synth.gsfc.nasa.gov).

Publisher Item Identifier S 0196-2892(02)04604-1.

These approximations are reasonable because B is slowly varying with altitude and because there is little curvature of the ray path. In (2), B is in tesla, Ω_F is in degrees, and VTEC $= \int N_e(z)\mathrm{dz}$ is the vertical total electron content at the sub-satellite point in total electron content units (10^{16} electrons/m^2).

It is clear from (1) and (2) that Faraday rotation depends on electron density and magnetic field and also on the orientation of the sensor with respect to the local magnetic field (i.e., on Θ_B). Examples of the effect of sensor orientation (scan pattern and look angle) can be found in [16]. For purposes of this paper, it will be assumed that the sensor looks to the right (i.e., across track in the plane perpendicular to the satellite heading). The sensor will be assumed to be in a sun-synchronous orbit with an altitude of 675 km, which is representative of orbits proposed for microwave remote sensing at L-band [4]. Faraday rotation will be computed using the International Reference Ionosphere (IRI-95) [17] to generate the necessary electron density profiles and the International Geomagnetic Reference Field (IGRF) [18] for the magnetic field.

V. Comments

Calculations have been presented here illustrating the effect of Faraday rotation and attenuation/emission from the ionosphere on passive microwave remote sensing at L-band (1.4 GHz). The motivation for this work is current interest in remote sensing of ocean salinity from space. To put the effects of the ionosphere into context, the change of brightness temperature with salinity is about 0.5 K/psu. It is clear from Figs. 2 and 3 (error due to Faraday rotation) and Tables II and III (error due to attenuation and emission) that corrections for these phenomena will have to be made to achieve salinity retrievals accurate to 0.1–0.2 psu.

The data also indicate some obvious choices for remote sensing. Clearly an optimum choice as far as minimizing errors is 6 am local time and as close to a minimum of solar activity as possible. Local time of 6 am is near the minimum in the daily cycle of the ionosphere, (Fig. 7 is an example of the diurnal variation). Remote sensing from a sun-synchronous orbit with an equatorial crossing time of 6am/6pm would provide observations near this minimum. Fig. 1 and Tables I–III illustrate the dependence on solar activity. For a fixed local time and location, Faraday rotation and emission/absorption increase roughly linearly with the solar activity (IG) index, Rz.

The studies presented here use the IRI-95 and are therefore representative of climatalogical data for the ionosphere. The IRI-95 model [17] is a good representation of mean characteristics of the ionosphere but is not a particularly good predictor of current (instantaneous) behavior [24], [25]. It may be possible to improve its ability to predict current behavior given input of local, measured parameters [26], [27]. However, without such input corrections for Faraday rotation and emission will likely have to be based on other models or techniques. (One possibility is to measure the third Stokes parameter [28].)

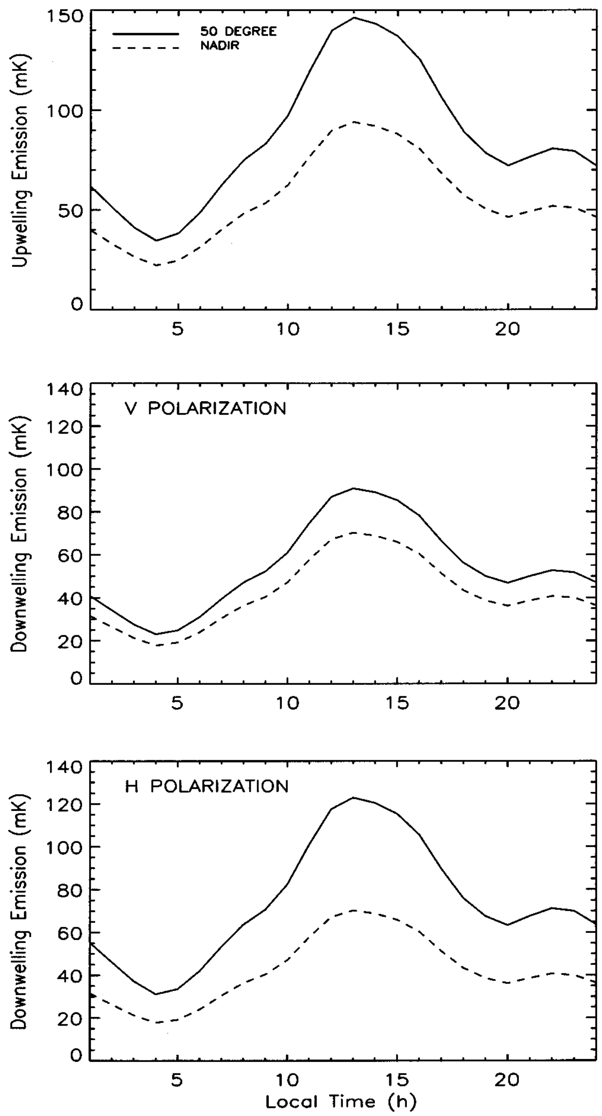

Fig. 7. Diurnal variation of upwelling (top) and downwelling emissions (vertical polarization, middle; horizontal polarization, bottom). The calculations are at 30 N, 330 E during high solar activity (June 1989). The surface is ocean with $S = 35$ psu and $T_0 = 20$ °C.

Attenuation is proportional to ν_z as in (7) which follows from the Appleton–Hartree equation and simplifications for L-band. This is a "cold" plasma approximation. In the present study, the collision frequency is taken as $\nu_z = \nu_{\mathrm{eff}}$ (see (9)–(10)). It has been suggested that, when $\nu \gg \nu_{\mathrm{eff}}$, as is the case at L-band, a better approximation is to use $\nu_z = 1.333\ \nu_{\mathrm{eff}}$ [29]. Hence, it is likely that the values for emission and loss given here are underestimated. Also, the results presented here employ approximations that are reasonable at low and middle latitudes. Near the poles, additional care must be taken in the calculation of attenuation [30].